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THE NASA POLLUTION-REDUCTION TECHNOLOGY PROGRAM FOR SMALL JET AIRCRAFT ENGINES - A STATUS REPORT

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Phase II: Combustor-Engine Compatibility Testing

The best two configurations of Phase I will be further refined to make these configurations ready for engine tests. Engine control systems will be designed, and performance parameters, such as combustor-exit temperature pattern factor, will be refined. One configuration will be selected for final refinement in preparation for the Phase III engine tests. This phase will take thirteen months.

Phase III: Combustor-Engine Demonstration Testing

The ability of the engine equipped with the selected combustor to meet the program emissions goals will be demonstrated. Phase III is expected to take approximately fifteen months.

The planned program schedule is shown in Table III. The Phase I contract was awarded in November 1974, and this phase was scheduled to be completed in June 1976. Phase II is scheduled for completion in mid-1977, and Phase III near the end of 1978.

Phase I Testing

Testing Approach

Phase I testing was conducted in two segments: (1) a six-month screening period; and (2) a three-month optimization period. During the initial testing period, approximately six builds each of three combustor concepts were tested to determine those with the greatest potential for meeting the program emissions goals. The screening was done almost solely on the basis of emissions results, with only minimal performance requirements. In general, screening was done only at the taxi-idle and sea-level takeoff operating conditions. For the refinement testing, two of the best configurations were chosen for more detailed testing over the EPA LTO cycle, and to document altitude relight capability.

All combustor rig testing is being done in a full-scale annular test rig. All combustor pressure, temperature, and velocity conditions are identical with those of the engine with the exception of pressure at the climbout and takeoff conditions (Table IV). Test rig pressure is limited to 41 N/cm^2 (60 $lbf/in.^2$) at those two conditions, as compared with the actual engine pressure of 138 N/cm^2 (200 $lbf/in.^2$) at takeoff.

The three combustor concepts selected for screening testing were chosen to have varying degrees of developmental difficulty and risk; correspondingly, they also have varying potential for achieving the program goals.

Concept 1 - Retrofittable Modifications to the Production TFE 731-2 Combustor
Concept 2 - Air-assisted/Airblast Fuel System
Concept 3 - Piloted Premixing/Prevaporizing Fuel System

Concept 1 Baseline Combustor

Description - Concept 1 (fig. 2) involves the types of changes which could be retrofitted to existing engines. This concept has very little developmental risk, and was considered to have the lowest potential of the three concepts for meeting the program goals for CO, HC, and NO_x simultaneously. The intent of testing this concept was to establish the levels of emissions reductions achievable without significantly altering the combustor and engine. The Concept 1 Baseline design uses a standard production combustor liner and standard production duplex fuel nozzles, with provision for

- Bleeding of up to 22% of combustor airflow at taxi-idle through a bleed screen (for uniformity of flow) and two bleed ports
- Introduction of air-assist air through the secondary fuel passages of the duplex fuel nozzles at taxi-idle
- Water-methanol injection through the fuel nozzle swirlers at takeoff

Test Results - The effects of bleed and air-assist on taxi-idle emissions were determined both separately and in conjunction. Figure 3 summarizes the more significant CO results. The maximum air-assist flow rate available, 0.36 kg/min (0.8 lbm/min), which is 0.27% of total combustor airflow, caused a significant reduction in the CO emission index, but not enough to meet the program goal.

The term "air-assist" refers to the use of high-pressure air injected into the fuel stream, as it leaves the fuel nozzle, to aid in fuel atomization. In some cases, the air is injected only at low-power operating points, through the secondary fuel passage of a duplex fuel nozzle, as in Concept 1. In other cases, the nozzle is designed with a passage specifically for air-assist air, as in Concept 2, and air-assist may be used at all operating conditions, if desired. In an engine, this air would be bled from the compressor and run through a supercharger to achieve the necessary pressure. The amount of air used in this manner is usually less than 0.5% of the total combustor airflow. Later in this paper, the term "airblast" is used. This refers to the use of air at the normal compressor-discharge conditions to aid in fuel atomization by utilizing the kinetic energy of the air stream. This air typically enters the combustor through an annular passage around a pilot fuel nozzle. It is in use at all operating conditions, and may have a secondary fuel flow into the airblast passage at high-power operating conditions.

As stated earlier, the goals of this program are in terms of the EPA emissions parameter, taken over a complete Landing-Takeoff Cycle. In this and subsequent figures, when the word "goal" is applied to an emission index (grams of pollutant per kilogram of fuel burned), it is a calculated value of the emission index which, at the operating condition under consideration, will satisfy the EPA parameter, assuming that the emission indices of the pollutant do not change at other operating points. For example, the goal of 30 for the CO emission index at taxi-idle in figure 3 indicates that, with present TFE 731-2 emissions as a base, as changes are made to reduce CO, a reduction of the CO emission index at taxi-idle to 30 will be sufficient to meet the EPA LTO cycle emissions standard, assuming that nothing has been done which increases the CO emission indices at approach, climbout, and takeoff. The calculated emission index goal may vary somewhat, depending on the particular engine or group of engines from which data were taken as a base. The goal for NO_x has been adjusted downward to take into account the fact that rig tests at high-power points

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Abstract

A three-phase experimental program is described which has the objective of enabling EPA Class T1 jet engines to meet the 1979 EPA emissions standards. In Phase I, three advanced combustor concepts, designed for the AiResearch TFE 731-2 turbofan engine, were evaluated in screening tests. Goals for carbon monoxide and unburned hydrocarbons were met or closely approached with two of the concepts with relatively modest departures from conventional combustor design practices. A more advanced premixing/prevaporizing combustor, while appearing to have the potential for meeting the oxides of nitrogen goal as well, will require extensive development to make it a practical combustion system. Smoke Numbers for the two combustor concepts which will be carried forward into Phase II of the program were well within the EPA smoke standard. Phase II, Combustor-Engine Compatibility Testing, which is in its early stages, and planned Phase III, Combustor-Engine Demonstration Testing, are also described.

Introduction

The Environmental Protection Agency, in 1973, issued emissions standards for jet aircraft engines (ref. 1) which required substantial reductions in emissions of carbon monoxide (CO), total unburned hydrocarbons (HC), and oxides of nitrogen (NO_x) in the vicinity of airports, and established a Landing-Takeoff Cycle, representative of adverse airport traffic conditions, over which pollutant emissions were to be integrated. In response to the issuance of these standards, several programs were initiated by NASA to evolve and demonstrate advanced low-emissions combustor technology. This paper describes one of these programs, specifically directed to EPA Class T1 engines, which are used on small commercial aircraft. Experimental results of the program to date are summarized, and the remainder of the program is outlined.

Mr. T. W. Bruce, Mr. F. G. Davis, Mr. T. E. Kuhn and Dr. H. C. Mongia, all of the AiResearch Manufacturing Company of Arizona, provided the bulk of the effort required to accomplish the work described in this paper.

Program Objectives

The Pollution-Reduction Technology Program for Small Jet Aircraft Engines is a multi-year contracted effort administered by the NASA Lewis Research Center. The program objectives are:

1. To evolve the technology required to enable EPA Class T1 engines to meet the 1979 EPA emissions standards. The T1 class includes all jet engines with less than 35,600 N (8000 lbf) thrust.
2. To demonstrate the emissions reductions in full-scale engine tests.

Contractor and Engine Selection

The contractor selected, through competitive procurement, to do this work is the AiResearch Manufacturing Company of Arizona, and the engine toward which the effort is directed is their TFE 731-2 turbofan engine. This engine (fig. 1) is a 15,600-N (3500-lbf) thrust engine with a single-stage fan, a four-stage axial low-pressure compressor, and a single-stage centrifugal high-pressure compressor. The engine overall pressure ratio is 13.6. The combustor is of the reverse-flow type, with radial fuel injection. The single-stage high-pressure turbine and the three-stage low-pressure turbine are not cooled, although the TFE 731-3, a derivative of this engine with 16,500 N (3700 lbf) thrust, has a cooled high-pressure turbine rotor.

The TFE 731-2 engine is well-suited to this program for two major reasons:

1. It is typical of the more advanced designs of the T1 class of engines; thus, the technology acquired in this program will be applicable to other Class T1 engines, and possibly to engines of other classes.
2. The TFE 731-2 is in the early part of its production run, and is expected to be in production for a considerable period after the 1979 EPA emissions standards go into effect.

Required Emissions Reductions

The program goals, which are identical with the 1979 EPA emissions standards, are in terms of the EPA emissions parameter (EPAP), pounds pollutant/1000 pounds thrust hours/cycle. The cycle referred to is the EPA Landing-Takeoff (LTO) cycle (Table I), chosen to be representative of airport conditions at peak traffic times. The required emissions reductions are shown in Table II. The first line lists the mean values of the pollutants measured in AiResearch in-house tests of six TFE 731-2 engines. The 1979 EPA standards are shown on the second line, and the percentage reductions required to meet those standards are given by the third line. Later engine tests indicate that: (1) the NO_x value in the first line may be closer to 6.0 than to 5.0, requiring a reduction of approximately 40 percent; and (2) the Smoke Number slightly exceeds the program goal. Throughout the entire program to date, the Concept 1 Smoke Number has been, at the worst, no higher than in the production combustor, and the Concepts 2 and 3 Smoke Numbers have been well below the program goal; therefore, Smoke Number will not be discussed further in this paper.

Program Plan and Schedule

Phase I: Combustor Concept Screening

Six builds each of three combustor concepts were screened on the bases of emissions and minimal performance. Two of the best configurations were selected for refinement testing. Phase I was a nineteen-month effort.

were run at reduced operating pressure. Limited AiResearch in-house experimental data indicate that the exponent, n, in the expression

$$EI_{NO_X,design} = EI_{NO_X,measured}\left(\frac{P_{design}}{P_{measured}}\right)^n$$

is approximately 0.31, rather than the commonly-used 0.5. Using n = 0.31, the takeoff NO_x emission index goal of approximately 10 at engine pressure is reduced to approximately 7 at the maximum available rig pressure.

Figure 3 shows that the maximum amount of combustor air bleed, 22%, causes the CO emission index to closely approach the goal; however, this amount of bleed is not practical, as it would cause a large increase in fuel consumption to make up for the thrust loss caused by bleeding. A bleed rate of approximately 5% is considered to be acceptable for the TFE 731-2 engine. Tests were run in which various air-assist flow rates and bleed flow rates were used together. It can be seen in figure 3 that a bleed flow rate of 5.6% used in conjunction with an air-assist flow rate of 0.36 kg/min (0.8 lbm/min) gives approximately the same results as does 22% bleed used alone. Similar data were obtained for HC emissions at taxi-idle. All techniques caused the HC emission index to meet the program goal with a comfortable margin (fig. 4).

At the takeoff condition, a 70% water-30% methanol mixture was injected through the fuel nozzle swirlers to reduce NO_x. The reductions obtained with various injection rates, in terms of takeoff fuel flow rate, are shown in figure 5, and indicate that a water-methanol injection rate of approximately 74% of the fuel flow rate is sufficient to meet the program NO_x goal. The use of water injection to meet NO_x standards is not attractive from a logistics standpoint, and the added weight of the water and associated equipment could cause unacceptable payload decreases; however, it does not appear likely that any other relatively minor modifications to the production combustor will reduce NO_x sufficiently to meet the EPA standard.

Concept 1 Modifications

Description - Modifications made in subsequent builds of Concept 1:

Mod 1 - Fuel Staging at Idle
The twelve fuel nozzles were divided into four quadrants of three nozzles each, and only two opposite quadrants were fueled at idle. The objectives were to improve fuel atomization and to increase the fuel-air ratio in the areas in which combustion is occurring.

Mod 2 - Increased Swirler Airflow
The fuel nozzle swirler airflow area was increased. It was hoped that the increased airflow would aid in fuel atomization.

Mod 3 - Piloted Airblast Fuel Nozzles
This modification was intended to reduce NO_x emissions at takeoff. At taxi-idle, all fuel went through the pilot nozzle, with high-pressure air-assist air going through the airblast fuel passage in an effort to improve atomization of the pilot nozzle fuel flow.

Mod 4 - Improved Recirculation Pattern
Hole pattern changes were made in the primary zone based on results from earlier AiResearch tests, which produced low CO and HC values.

Mod 5 - Variable Primary-Zone Equivalence Ratio
This was a more extensive combustor liner change, made after it had become clear that the other Concept 1 techniques, with the exception of water injection, would not significantly lower NO_x. Swirlers were added to the combustor dome to lower the primary-zone equivalence ratio at takeoff. Grommets were installed to block off the swirlers at taxi-idle to provide a stoichiometric primary-zone fuel-air ratio, simulating a variable-geometry device. This modification was taken from Concept 2.

Test Results - The CO and NO_x results for these five modifications are summarized in figure 6. Some of these results reflect the use of air-assist. None of these modifications was considered to be an overall improvement over the Baseline Combustor; however, one of them, Mod 3, is noteworthy. The use of a piloted airblast fuel nozzle reduced takeoff NO_x by 55% of the required amount. Since only the pilot nozzle receives fuel at taxi-idle, air-assist air was put through the fuel passage of the airblast portion of the nozzle in an effort to improve atomization of the pilot fuel nozzle. This had a smaller-than-expected effect on CO production, reducing it by 32% of the required reduction. It was speculated that the high-pressure air-assist air, upon mixing with the lower-pressure airblast air prior to approaching the pilot-nozzle fuel stress, was completely losing its effectiveness. It is possible that, through use of a nozzle properly designed to use air-assist (this nozzle was not intended to do this), CO might be reduced as in the Baseline Combustor, along with a very significant NO_x reduction brought about by the airblast feature. This approach was not pursued for two reasons: (1) the time required to obtain such a nozzle would have been prohibitive, and (2) this approach is essentially the same as that used in Concept 2, and if the air-assist/airblast fuel system is successful in Concept 2, the implementation of that technology could be pursued by the individual engine manufacturers.

Summary of Concept 1 Test Results - To summarize the results of Concept 1 testing:

- The program taxi-idle CO goal was very closely approached through the use of a moderate amount (5.6%) of combustor air bleed in conjunction with an air-assist flow rate of 0.36 kg/min (0.8 lbm/min), which is 0.27% of total combustor airflow
- The program taxi-idle HC goal was met with a considerable margin through the use of bleed, air-assist, or a combination of both
- The program takeoff NO_x goal was met by use of water-methanol injection, a technique which is not acceptable as a practical solution. The only "dry" technique available, the use of a piloted airblast fuel nozzle, reduced NO_x by 55% of the required amount, but had high CO at taxi-idle.

Concept 2 Baseline Combustor

Description - Concept 2 (fig. 7) is a moderate departure from the production combustor. Both the developmental risk and the potential for achieving the program goals were considered greater than for Concept 1, but much less than for Concept 3. The Concept 2 Baseline Combustor uses an increased number of fuel nozzles (twenty as compared with twelve in the production combustor) which are inserted through the combustor dome. These nozzles are combination air-assist/airblast nozzles. The airblast feature is in effect at all operating conditions, while the air-assist feature may be used as required, principally at the taxi-idle condition. The fuel nozzle swirlers are replaced by grommets (fig. 8) at low-power operating points to simulate a proposed variable-geometry device designed to regulate swirler airflow. The intent of this design is to minimize CO production at taxi-idle by maintaining a stoichiometric primary-zone fuel-air ratio, then opening up the swirlers at takeoff to reduce the primary-zone equivalence ratio to 0.6 to 0.7 to minimize NO_x production.

Test Results - The Concept 2 Baseline Combustor exhibited excellent taxi-idle CO and HC characteristics (figs. 9 and 10), easily meeting the program goals for both; however, the takeoff NO_x emission index was 13.7, slightly higher than that of the production combustor. It was believed that the primary zone was operating at a much higher equivalence ratio than that for which it was designed. This belief was confirmed by a test in which taxi-idle conditions were run with swirlers instead of with grommets. Although CO production was increased somewhat (fig. 9), it did not deteriorate nearly as much as would be expected at an equivalence ratio well below 1.0. In fact, the CO emission index with 0.64 kg/min (1.4 lbm/min) air-assist flow was 28.2, which still met the program goal.

Concept 2 Modifications: Description and Test Results

Several combustor modifications were made in an attempt to reduce takeoff NO_x while retaining the excellent taxi-idle CO and HC characteristics of the baseline combustor.

Mod 1 - Liner Hole Pattern Change - A row of primary-zone orifices on both the inner and outer combustor liners was moved upstream to have an early-quench effect on NO_x reactions, and the holes were enlarged to reduce the primary-zone equivalence ratio.

The CO and NO_x results of this and subsequent modifications are presented in figure 11. In cases in which data were taken both with swirlers and with grommets, the letters "S" and "G" are used to denote this. Varying amounts of air-assist air were used, at takeoff conditions as well as at taxi-idle conditions. HC results are not shown, as they met the program goal in all cases.

For Mod 1, it can be seen that a significant reduction in the takeoff NO_x emission index was achieved, but this was accompanied by a similar-sized increase in the CO emission index at taxi-idle.

Mod 2 - Liner Hole Pattern Changes and Swirler Change - Thermocouple data and visual observations indicated high-temperature regions near the outer liner of the combustor. Circumferentially, the temperature near the outer liner corresponded with the NO_x emission index at that location. A row of primary-zone holes was added to the outer combustor liner only. These holes were sized to allow air to penetrate only far enough into the hot gas stream to quench the suspected NO_x reactions near the combustor outer liner, and not far enough to quench CO reactions in the combustor recirculation zone. Also, swirlers with a 50% increase in airflow capacity were installed to further reduce the primary-zone equivalence ratio at takeoff.

Figure 11 shows that this modification was fairly successful, lowering the takeoff NO_x emission index to 7.9, with only a slight increase in taxi-idle CO.

Mod 3 - Liner Hole Pattern Change and Swirler Change - Data taken both with the larger swirlers and with the smaller swirlers indicated that the recently-achieved NO_x reductions were a result of the addition of the small holes to the outer combustor liner, and not a result of increased swirler flow. Since circumferential temperature-NO_x data indicated that further NO_x reductions might be available in this area, the small holes used in Mod 2 were doubled in number and decreased in size to confine penetration to the near-wall region. They were also moved upstream for earlier NO_x-reaction quenching. The larger primary-zone holes were moved downstream to their original position in the baseline combustor because it was thought that their present upstream position might be encouraging CO production. For the same reason, the original small swirlers were reinstalled. The net result of these changes is a reliance on the small outer liner holes to curtail NO_x production in high-temperature regions, and not on a lean primary zone.

Figure 11 shows that the CO emission index was reduced somewhat, but the effect on NO_x was unexpected. With Mod 2, the NO_x emission index with grommets was higher than that with swirlers, as expected. With this modification, however, the situation was reversed, and the NO_x emission index with grommets was noticeably lower than that with swirlers. It was speculated that, while the average primary-zone fuel-air ratio is leaner in the swirler configuration, in the outer wall region combustion is occurring in a locally richer area. The swirler airflow sweeps the wall with a high-velocity layer of air, deflecting the small outer liner jets and preventing their pentration into the reaction region. It appears that the small jets were not doing their intended job of quenching NO_x reactions, and in fact, this configuration had a takeoff NO_x emission index nearly identical with that of Mod 1, which had no small orifices on the outer liner.

In the grommet configuration, it was speculated that combustion took place in two zones. In the first zone, extending from the combustor dome to the discharge of the primary-zone cooling band, combustion occurs with an extremely rich fuel-air ratio at a relatively low flame temperature, with a low NO_x-formation rate. In the second zone, a large amount of air is introduced to provide a lean mixture, again maintaining a low NO_x level. Although the grommet configuration provided the lowest NO_x emission index obtained with Concept 2, the rich-burning-zone approach could be expected to cause

carbon-buildup problems when run for a lengthy time period.

Mod 4 - Liner Hole Pattern Change and Cooling Air Change - The small outer-liner primary-zone orifices were reduced in number and increased in size to increase their jet momentum while retaining the same total area. They were also moved slightly downstream to lessen the deflection effect of the swirler air. The large outer-liner primary-zone orifices were moved further downstream to reduce quenching of taxi-idle pollutants. For the same reason, primary-zone cooling air was reduced by 33 percent. The CO emission index closely approached the program goal, while the NO_x emission index (with swirlers) remained approximately the same as it was in Mod 3.

Mod 5 - Liner Hole Pattern Change, Cooling Air Change, and Swirler Change - Since Mod 2 had given the lowest Concept 2 NO_x value with swirlers, Mod 5 was conceived as an extension of Mod 2 with the results of Mods 3 and 4 also considered. As a result, the small outer-liner primary-zone orifices were reduced in number, increased slightly in size, moved slightly downstream, to the same axial position as the larger primary-zone orifices, and made plunged instead of flush, in order to produce jets capable of penetrating the high-momentum layer of cooling and swirler air near the outer liner. Also, the larger swirlers were reinstalled, and the primary-zone cooling air, which had been reduced in Mod 4, was restored to the original amount. It was anticipated that the primary zone would be slightly leaner than in Mod 2. This did not turn out to be the case. Not only was takeoff NO_x slightly higher than in Mod 2, but CO was very high. Furthermore, CO with swirlers was much lower than with grommets. Both facts indicate that the primary zone was much richer than intended. Carbon buildup was in evidence.

It is difficult, looking at the data presented in figure 11, to say with any assurance whether any real progress in overall emissions reduction has been achieved, or if only tradeoffs between CO and NO_x have been made. Figure 12 is a useful way of presenting such data. Note that the variables plotted are taxi-idle CO (with grommets) versus takeoff NO_x (with swirlers), and not CO and NO_x at a common point, as suggested in ref. 2. In figure 12, if the data points for various modifications of a combustor fall on a common line, it indicates that only CO-NO_x tradeoffs are occurring. Real progress in emissions reduction are indicated by a shifting of the data toward the "origin" of the plot. The Concept 2 data of figure 12, while having some scatter, generally fall on a line, indicating that the modifications made to the baseline combustor traded CO at taxi-idle for NO_x at takeoff, and vice-versa; however, the improvement over the production combustor is clear. From figure 12, one can draw the conclusion that, in the absence of significant modification, Concept 2 is not likely to meet the program goals for CO and NO_x simultaneously without resorting to water injection to reduce NO_x at takeoff. At the time this paper was written, Phase I refinement testing remained to be done, as well as Phase II refinement and optimization testing. It was hoped that modifications made during this testing would reduce takeoff NO_x sufficiently to allow both CO and NO_x goals to be met.

Summary of Concept 2 Test Results - To summarize the results of Concept 2 testing:

- The program goals for taxi-idle CO and HC can be met with considerable margins through the use of air-assist, for which the Concept 2 fuel nozzle is designed.
- Takeoff NO_x can be reduced somewhat, but only at the expense of taxi-idle CO. Even then, the program NO_x goal was not met in any configuration, and is not likely, without significant combustor modifications, to be met with a "dry" approach.
- The combined reduction in taxi-idle CO and takeoff NO_x through the use of air-assist and airblast, respectively, makes Concept 2 a significant improvement over the production combustor.

Concept 3 Baseline Combustor and Modifications to Date

Description - Concept 3 (fig. 13) is a considerable departure from conventional combustor design practices. It was considered to have the highest potential for meeting the program goals for all pollutants simultaneously, and also the highest developmental difficulty and risk. The risk is inherent in premixing/prevaporizing combustors because a combustible mixture of fuel and air is present at some point prior to the desired combustion location. This mixture is subject to spontaneous ignition under certain combined conditions of pressure, temperature, and residence time in the premixing/prevaporizing chamber. The mixture may also be ignited by flashback if the velocity of the mixture is lower than the flame speed in the mixture. The developmental difficulty stems from the staged design used. The pilot zone is designed to operate alone at taxi-idle with a near-stoichiometric fuel-air ratio to minimize CO and HC emissions. The main burning zone is designed to operate at a low equivalence ratio to minimize NO_x emission at high-power conditions. Unfortunately, the low equivalence ratio tends to produce higher CO emission at takeoff than is customary with conventional combustors. This means that the CO at low-power conditions must be reduced even further in order to meet the overall LTO cycle goals. Serious difficulties occur at the approach condition with staged combustors. Since the pilot zone is designed to operate stoichiometrically, approach operation with the pilot zone alone may contribute a significant amount of NO_x to the LTO cycle, something not found in conventional combustors. In addition, it may be a questionable practice, from a safety standpoint, to go into approach with the main combustion zone not burning. In the event of an aborted landing, the main burning zone would have to be capable of lighting off and bringing the engine up to full power in an extremely short time. Any delay in ignition could not be tolerated. On the other hand, if a small amount of fuel is kept burning in the main combustion zone at approach, assuming that stable combustion could be maintained, poor combustion efficiency will cause some amount of CO and HC emissions, which may or may not be offset by reduced CO and HC in the efficiently-burning pilot zone. The Concept 3 Baseline Combustor pilot zone uses twenty simplex fuel nozzles. Since these nozzles must be able to flow enough fuel for the approach condition, atomization at taxi-idle is not optimized. The main combustion zone has forty in-

dividual premixing/prevaporizing tubes. These tubes were external to the combustor during early testing to facilitate changes in fuel-injection length. Separately-measured and controlled air, heated to the same temperature as the remaining combustion air, was used in the premixing/prevaporizing tubes. Simplex fuel nozzles were used for liquid fule injection.

Initial tests were made using gaseous propane fuel in the main combustion zone. The flame temperature of propane is similar to that of vaporized Jet-A fuel, and NO_x data obtained with gaseous propane should indicate the maximum emissions reductions to be expected with perfectly-vaporized Jet-A fuel. In all tests, Jet-A fuel was used in the pilot zone.

Early testing with propane was aimed at establishing optimum fuel and air splits between the pilot zone and the main burning zone at takeoff. Parametric data were taken with varying fuel splits, air splits, premix tube equivalence ratio, and premix tube velocity. Fuel-injection length was held constant at 0.20 meters (8 in.). The best combination of flows was found to be:

- Pilot zone fuel flow of 68 kg/hr (150 lbm/hr), which is 30% of the total fuel flow
- Premix tube airflow 24% of total combustor airflow

From the above, it follows that:

- Premix tube equivalence ratio was approximately 0.66
- Premix tube velocity was approximately 107 m/sec (350 ft/sec)
- Premix tube residence time, with 0.20 m (8 in.) injection length, was 1.9 milliseconds

In addition to the Concept 3 Baseline Combustor, two modifications have been tested:

Mod 1 - The pilot-zone air orifices on the outer liner were increased in number from 40 to 120 to quench NO_x reactions in hot gases which were thought to be escaping between the more widely spaced orifices. Pilot-zone cooling-air holes on both the outer and inner liners were closed off to offset the anticipated CO increase.

Mod 2 - Transpiration cooling holes were added to the inner-liner ramp between the pilot and main burning zones. Hot spots had been observed on the inner liner directly across from the premix tube openings on the outer liner.

Test Results - Results of testing with propane at the takeoff condition are presented in figure 14. In the case in which a 0.28-m (11-in.) fuel-injection length was used, instead of the usual 0.20 m (8 in.), the NO_x emission index decreased significantly, but the CO and HC emissions indices increased. It is speculated that the improved mixing provided by the additional mixing length, while beneficial for NO_x reduction, is detrimental to CO and HC reduction for the same reason, namely that local volumes of higher-than-average equivalence ratio are not as prominent. Another point of interest (marked with *) in figure 14 involves a test in which three changes were made:

- The propane distribution and injection system was improved
- The pilot-zone simplex fuel nozzles were changed from ones with a flow number of 0.9 to ones with a flow number of 0.7
- Larger premix tubes were used which lowered the premix tube velocity from 107 m/sec (350 ft/sec) to 91 m/sec (300 ft/sec)

The combined effect of these changes on takeoff CO and HC as compared with previous data with 0.20-m (8-in.) premix tubes, is dramatic, and a 20% reduction in NO_x was also obtained. While the NO_x decrease may have been caused by the increased premix tube residence time and the improved propane distribution, the CO and HC decreases are almost certainly caused by the improved atomization of the smaller pilot-zone fuel nozzles. This encourages the idea of adding an air-assist/airblast type fuel nozzle to the Concept 3 Combustor during Phase II of this program.

Tests were run at the takeoff condition using Jet-A fuel in the main burning zone. Again, parametric data were taken. Results of three tests run at the same flow splits as used in the propane tests, but with varying premix tube lengths and velocities, are shown in figure 14. These tests were all made with the Mod 2 configuration. The CO and HC emissions indices are high relative to those obtained with propane at similar conditions, but NO_x is lower, even when a mixing length of only 0.08 m (3 in.) is used with a velocity of 107 m/sec (350 ft/sec). If all the Mod 2 NO_x emission index data from figure 14 are plotted versus premix tube residence time to rationalize the varying tube velocities and lengths (fig. 15), an interesting point emerges. It appears that a change in premix tube residence time has a much greater effect on the NO_x emission index when using gaseous propane fuel than when using liquid Jet-A fuel. This is an unexpected result which seems reasonable only if it is assumed that the liquid fuel injectors are doing a much better job of getting the Jet-A fuel into the premix tube airstream in a well-mixed manner than the propane injectors are doing with the gaseous fuel.

Test results at taxi-idle with the same air split between pilot and main burning zones, and with all fuel burning in the pilot zone, are shown in figure 16. The improvement in the CO and HC emissions indices when the smaller (and presumably better-atomizing) fuel nozzle was used is nearly as dramatic as it was at the takeoff condition. Both emissions indices were well below the program goals for the taxi-idle condition, and offer the opportunity to offset higher-than-usual CO and HC values at higher-power points in the Landing-Takeoff Cycle. Taxi-idle NO_x data are included in figure 16 because the values are slightly higher than those of Concepts 1 and 2, and to show that the values have not been affected by combustor modifications which affected CO and HC.

Summary of Concept 3 Test Results - Incomplete screening tests of the Concept 3 Combustor have

produced the following results:

- NO_x emission indices at takeoff were well within the program goal
- CO and HC emissions indices at taxi-idle, which had been slightly above the program goals, were reduced to values well below the program goals through the use of a smaller pilot-zone fuel nozzle
- CO and HC emissions indices at takeoff were somewhat higher than those obtained with Concepts 1 and 2; however, in tests with propane used in the main burning zone, CO and HC emissions were significantly reduced through the use of a smaller pilot-zone fuel nozzle

Remaining Concept 3 Screening Tests - At the time this paper was written, several Concept 3 modifications remained to be run during the initial screening testing period. Mod 3 was to be run at the approach and climbout conditions to determine whether any severe problems exist at those operating points. Following that test, the premixing/prevaporizing tubes were to be redesigned. Up to this point, the tubes and their air supply had been external to the combustor housing for convenience in making changes without combustor disassembly; however, it was considered important to test a configuration during Phase I which better simulated actual engine hardware, which would have a premixing/prevaporizing system entirely within the combustor housing. Mods 4 and 5 were to be tested with the internal design.

Refinement Testing - Concepts 2 and 3 were chosen for further testing during the refinement testing period of Phase I. Each combustor was to undergo a test, a modification, and a retest over the complete EPA Landing-Takeoff Cycle to completely document the emissions characteristics of each combustor. In addition, altitude relight performance was to be documented at actual altitude conditions during this testing.

Phase II

Combustor Selection - Two of the best configurations of Phase I will be chosen from the following:

- Concept 2
- Concept 3
- A combination of Concepts 2 and 3

Combustor Refinement Testing

Test Objectives - The two selected combustor configurations will undergo a series of tests, design modifications, and retests over a five-month period, with the following objectives:

1. Optimization and combination of the best pollution-reduction features determined in Phase I

2. Combustor performance optimization to assess the compatibility of each combustor type with the TFE 731-2 engine. Performance parameters for optimization will include:

- Combustor-exit temperature distribution, both local (pattern factor) and aggregate (radial and circumferential profiles)
- Wall temperature measurements to estimate durability
- Carbon deposition
- Fuel staging at cut-in and cut-off points between engine power settings, and effect of staging methods on combustion stability
- Combustor pressure loss
- Altitude relight performance
- Lean stability limits over simulated engine operating range

Test Conditions - Phase II refinement testing conditions will include the following:

- The EPA Landing-Takeoff Cycle
- Altitude cruise at 12,200 m (40,000 ft) and Mach 0.8
- Altitude relight at applicable conditions

Combustor Optimization Testing - The most promising combustor configuration from the Phase II refinement testing will be selected for additional testing over a two-month period to optimize its compatibility with the TFE 731-2 engine.

Phase III

The optimized most promising combustor configuration from Phase II will be tested as part of a complete TFE 731-2 engine. The objectives of the Phase III Combustor-Engine Demonstration Testing will be:

- To demonstrate that the emissions reductions achieved in the test rig are actually realized in the engine when the new technology is applied to the engine
- To determine whether engine performance in such areas as acceleration and altitude relight capability is satisfactory
- To determine whether the combustor will hold up structurally in the engine environment, and whether it will affect other engine components adversely

Concluding Remarks

1. The program goal for taxi-idle CO emission was met or closely approached by all three combustor concepts.
2. The program goal for taxi-idle HC emission was met with a considerable margin by all three combustor concepts.
3. The program goal for takeoff NO_x can be met with Concept 1 only through the use of water injection, which is not a desirable technique. In Concept 2, no configuration met the goal; however, one configuration (Mod 4), which very closely approached the taxi-idle CO goal and met the HC goal, gave a reduction in takeoff NO_x of 53% of the required amount. It is assumed that the use of water injection would allow Concept 2 to meet the takeoff NO_x goal, although this technique was not tested in Concept 2.
4. Concept 3 appears to have the potential for meeting the program goals for all pollutants simultaneously; however, extensive development will be required to make a premixing/prevaporizing

combustor into a practical combustion system.

5. The Smoke Number for Concept 1 was, at the worst, no higher than in the production combustor, which was slightly above the program goal. For Concepts 2 and 3, which will be carried forward into Phase II of the program, Smoke Numbers were well below the program goal.

References

1. "Control of Air Pollution for Aircraft Engines - Emission Standards and Test Procedures for Aircraft," Federal Register, Vol. 38, No. 136, July 1973, pp. 19087-19103.

2. Verkamp, F. J., Verdouw, A. J., and Tomlinson, J. G., "Impact of Emissions Regulations on Future Gas Turbine Engine Combustors," AIAA Paper 73-1277, 1973, Las Vegas, Nev.

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TABLE I. - EPA LANDING-TAKEOFF CYCLE

Mode	Time in mode (minutes)	Engine power setting (percentage of rated power)
Taxi-idle (out)	19.0	5.7*
Takeoff	0.5	100
Climbout	2.5	90
Approach	4.5	30
Taxi-idle (in)	7.0	5.7*

*Manufacturer's recommended power setting of 890 N (200 lbf) thrust for taxi-idle operation.

TABLE II. - REQUIRED EMISSIONS REDUCTIONS

	EPA emissions parameter lbm/1000 lbf thrust-hr/cycle			SAE smoke number
	CO	HC	NO_x	
Mean level of six engines	17.5	6.6	5.0	36
EPA 1979 standards and program goals	9.4	1.6	3.7	40
Percentage reduction required	46	76	26	--

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TABLE III. - PROGRAM SCHEDULE

Program phase		Calendar year				
		1974	1975	1976	1977	1978
Phase I:	Combustor concept screening					
Phase II:	Combustor-engine compatibility testing					
Phase III:	Combustor-engine demonstration testing					

TABLE IV. - ENGINE OPERATING CONDITIONS

Mode	Thrust		P_{T3}		T_{T3}		T_{T4}		F/A	W_A	
	N	lbf	N/cm^2	lbf/in.^{2}	K	^oF	K	^oF		kg/sec	lbm/sec
Taxi-idle	890	200	20	29	365	198	722	841	0.0097	2.31	5.1
Takeoff	15 600	3,500	138	200*	669	744	1,224	1,743	0.0156	13.38	29.5*
Climbout	14 000	3,150	126	183*	652	714	1,187	1,677	0.0150	12.43	27.4*
Approach	4,700	1,050	52	75	500	440	945	1,242	0.0118	5.76	12.7

*Maximum test rig pressure is 41 N/cm^2 (50 lbf/in.^{2}). Actual airflow is scaled accordingly.

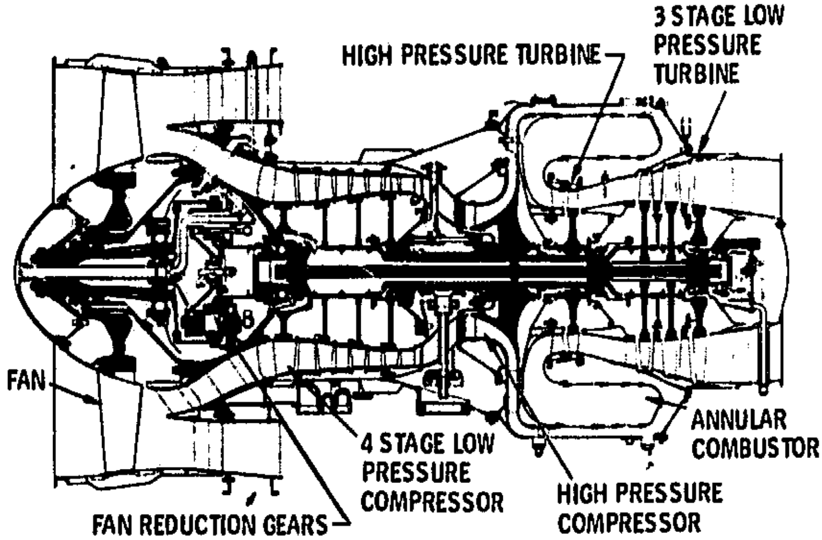

Figure 1. - AiResearch TFE 731-2 turbofan engine.

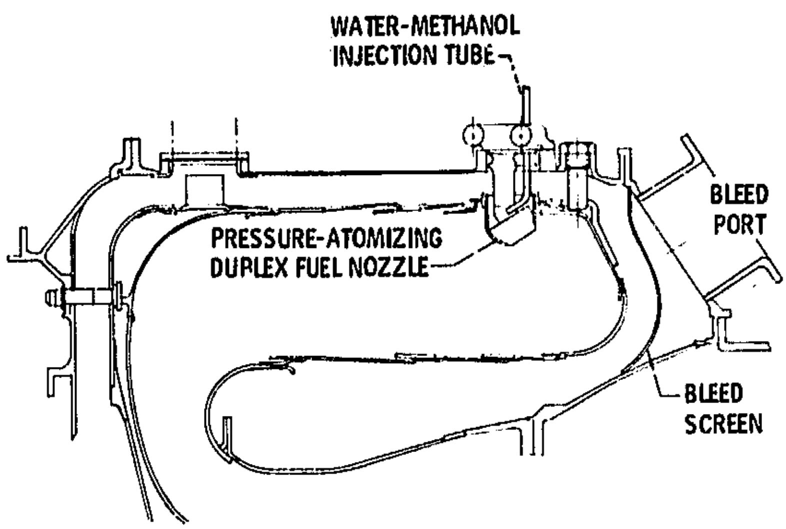

Figure 2. - Concept 1 baseline combustor.

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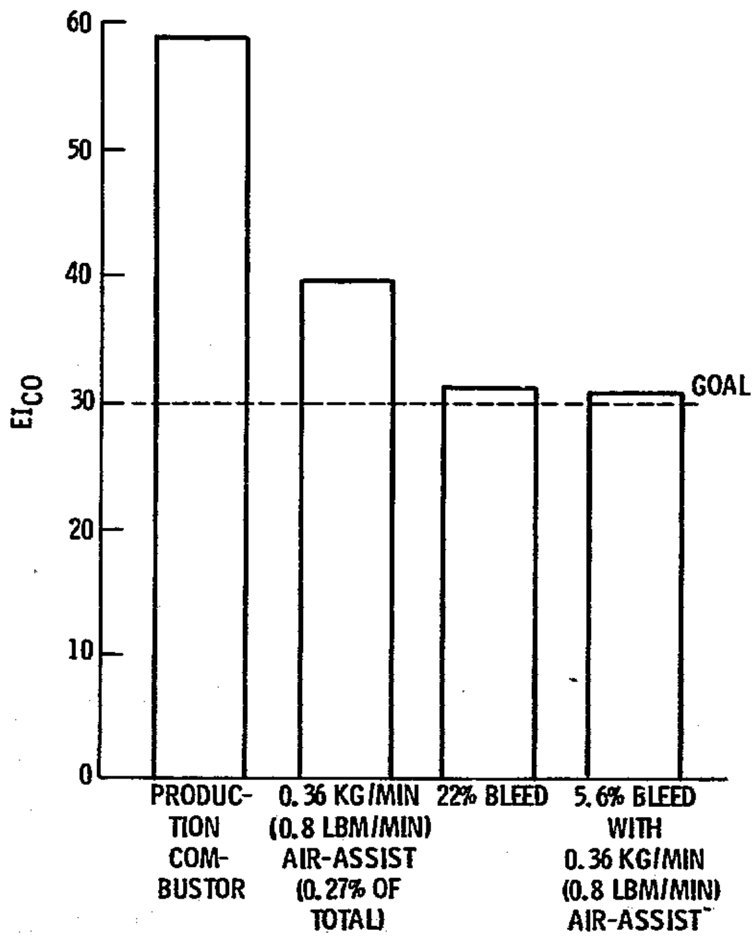

Figure 3. - Effects of air-assist and bleed on Concept 1 Baseline Combustor taxi-idle CO emission.

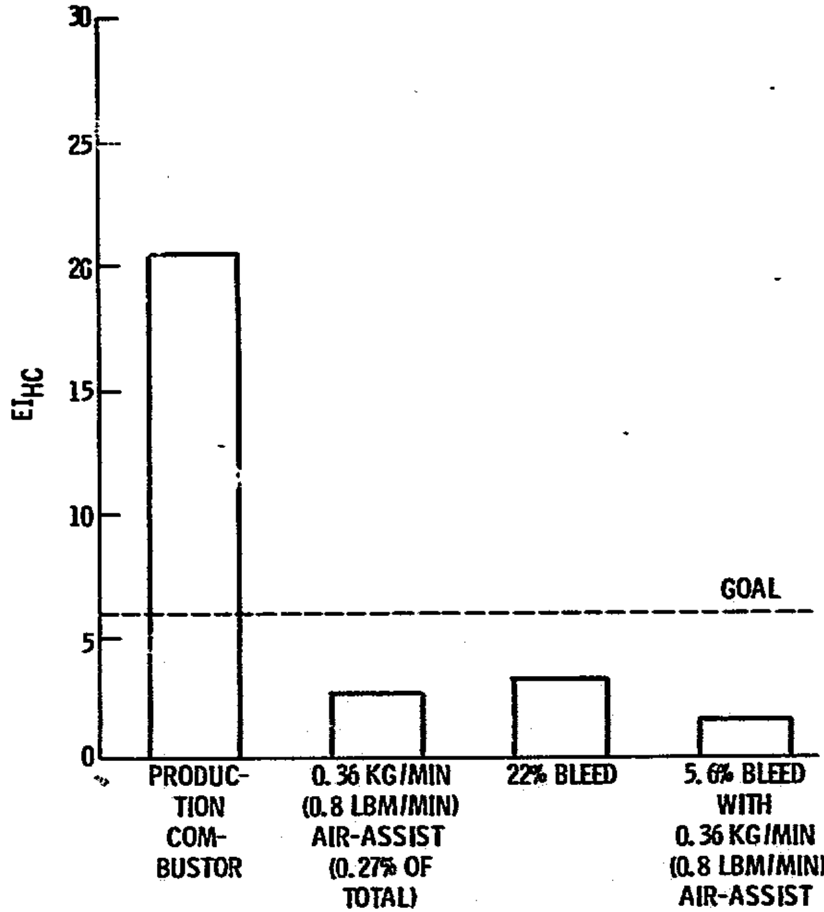

Figure 4. - Effects of air-assist and bleed on Concept 1 Baseline Combustor taxi-idle HC emission.

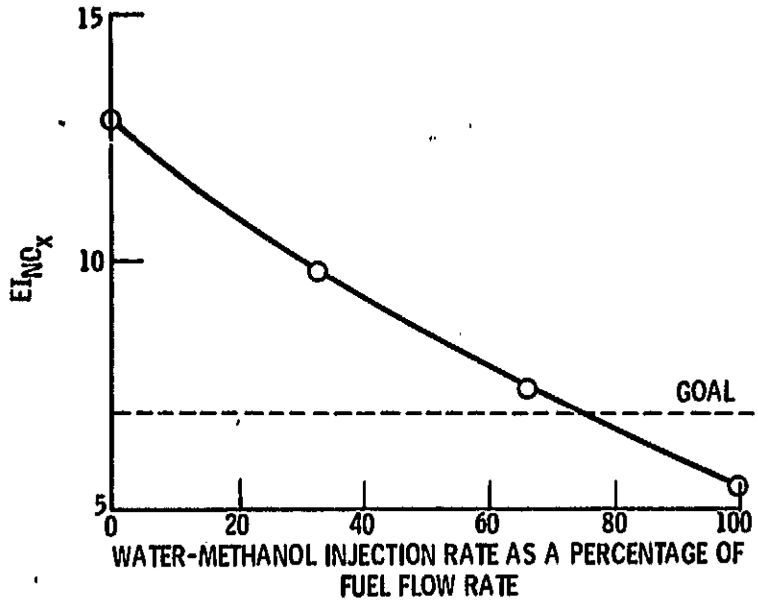

Figure 5. - Effect of water-methanol injection rate on Concept 1 Baseline Combustor takeoff NO_X emission.

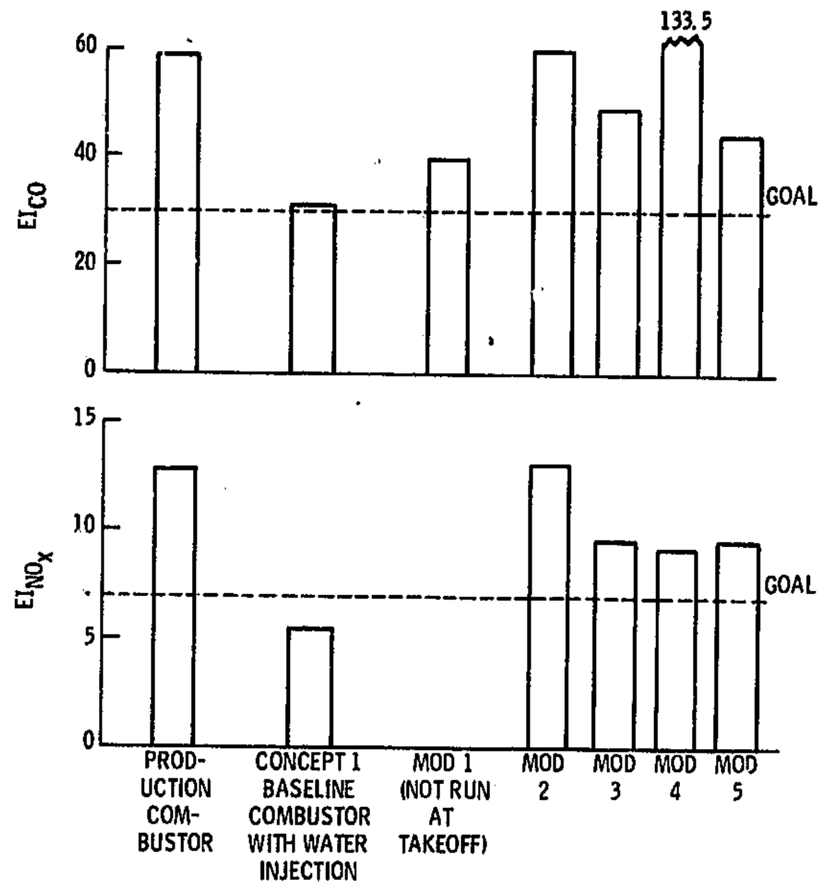

Figure 6. - Concept 1 taxi-idle CO and takeoff NO_X emissions.

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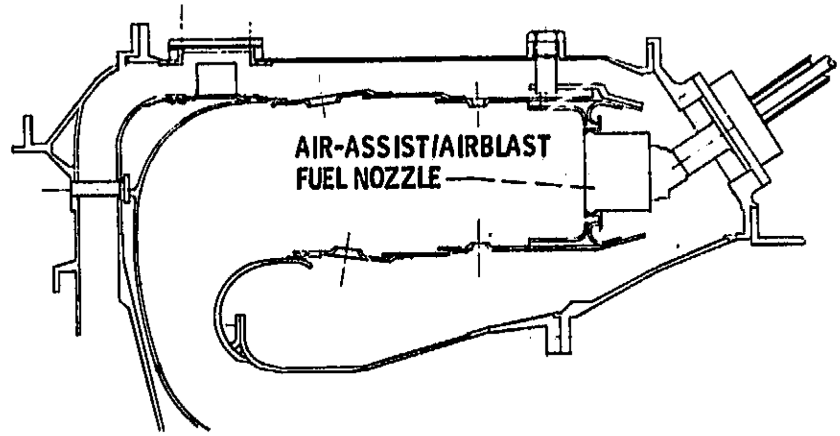


Figure 7. - Concept 2 baseline combustor.

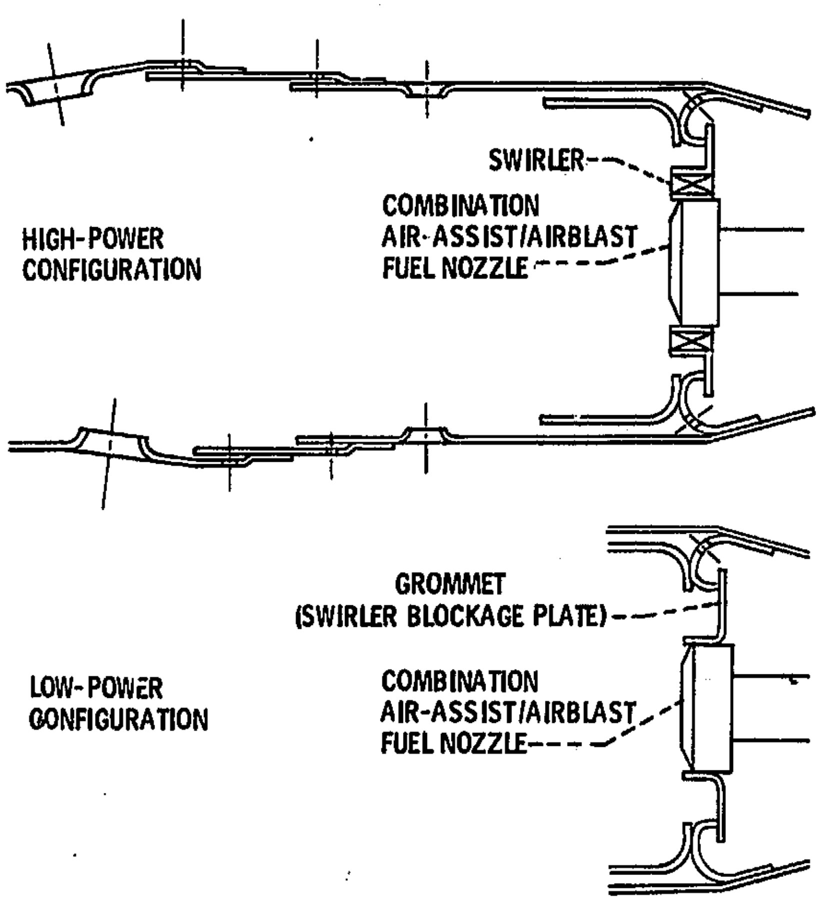


Figure 8. - Concept 2 baseline combustor showing installation of swirlers or grommets.

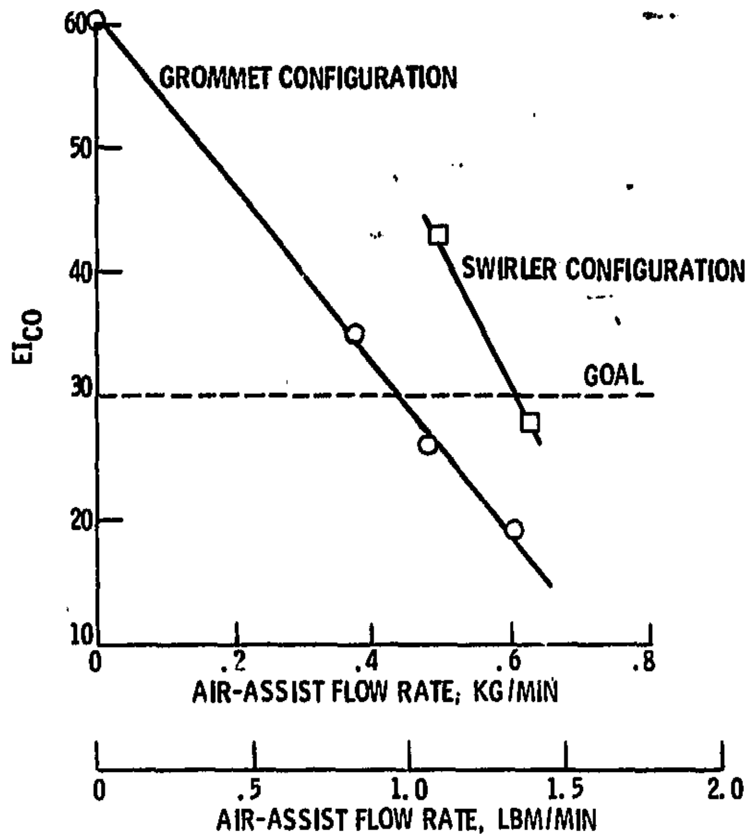


Figure 9. - Effect of air-assist flow rate on Concept 2 Baseline Combustor taxi-idle CO emission.

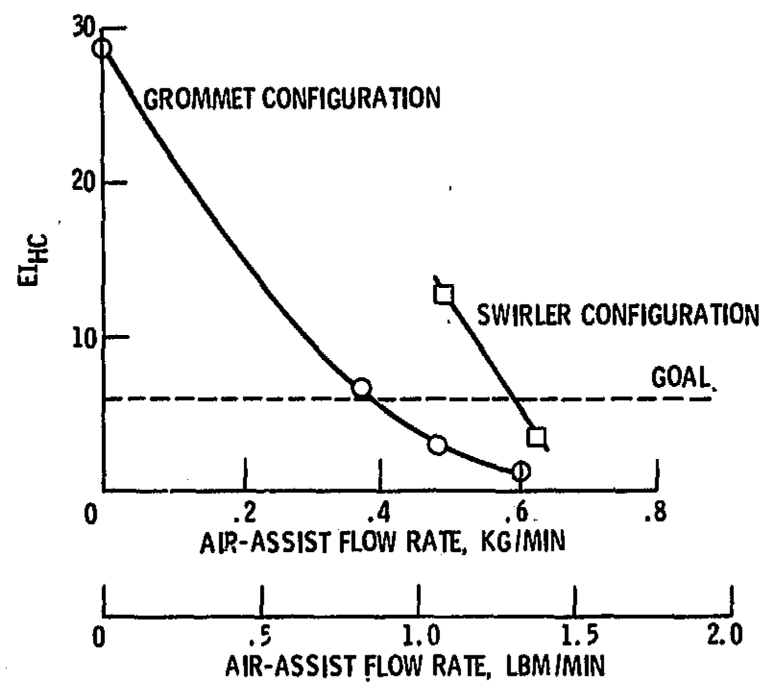


Figure 10. - Effect of air-assist flow rate on Concept 2 Baseline Combustor taxi-idle HC emission.

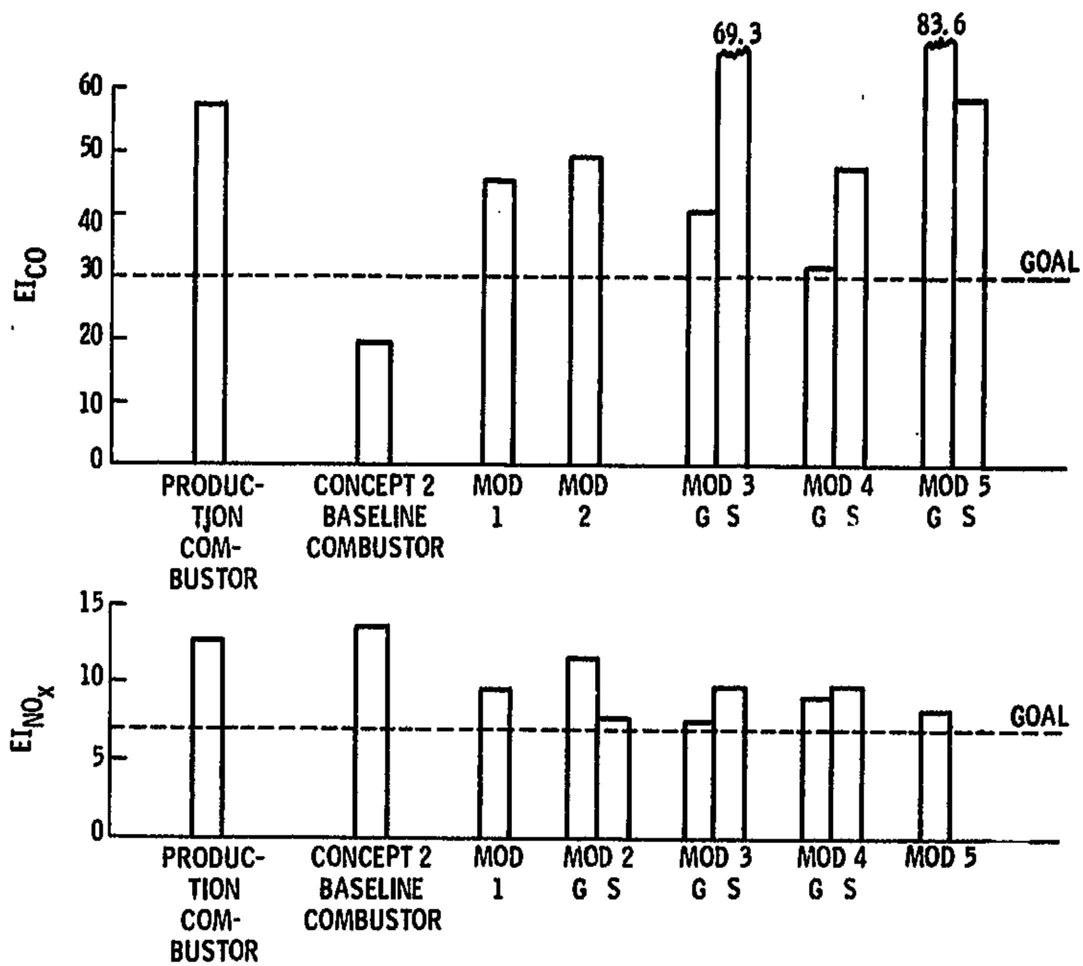


Figure 11. - Concept 2 taxi-idle CO and takeoff NO_X emissions.

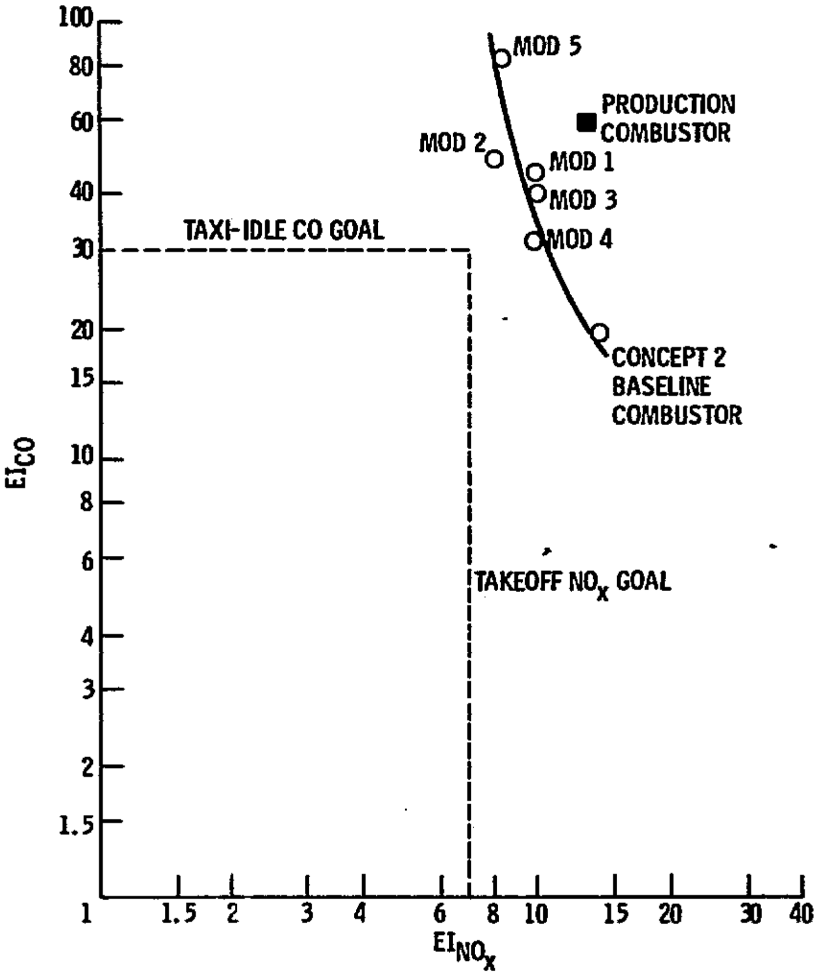


Figure 12. - Concept 2 taxi-idle CO and takeoff NO_x relationship.

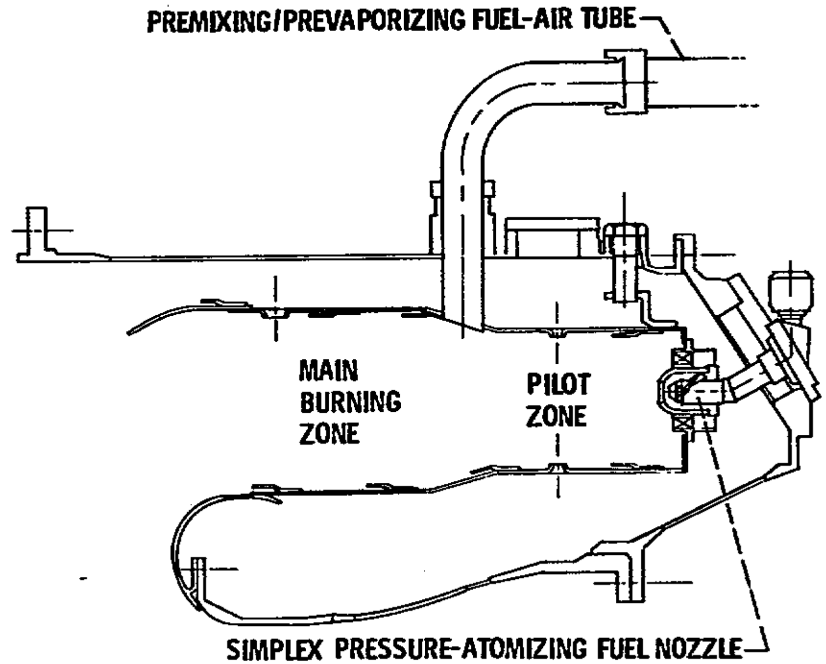
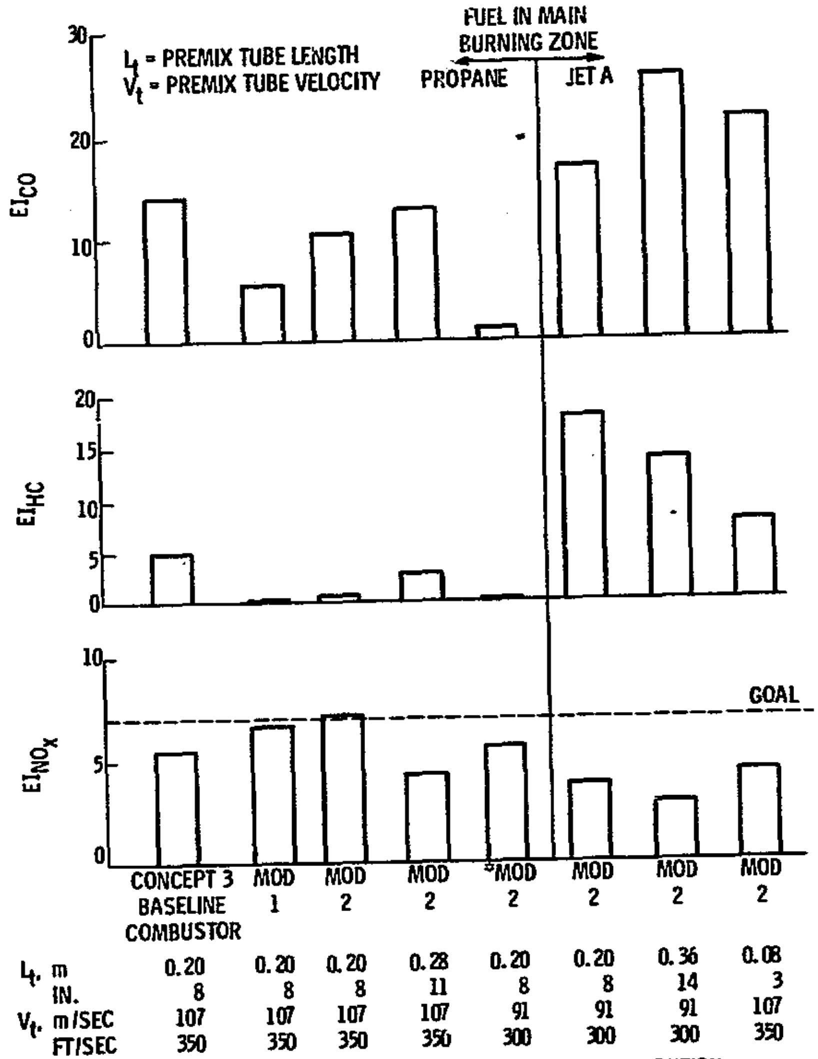


Figure 13. - Concept 3 baseline combustor.



*SMALLER PILOT-ZONE FUEL NOZZLE AND IMPROVED PROPANE DISTRIBUTION

Figure 14. - Concept 3 takeoff emissions at design fuel and air split conditions.

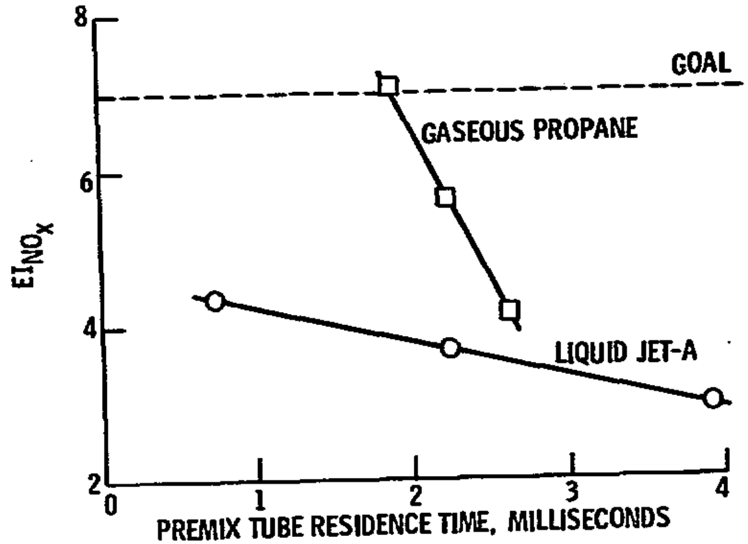


Figure 15. - Effect of premix tube residence time on Concept 3 Mod 2 takeoff NO_x emission.

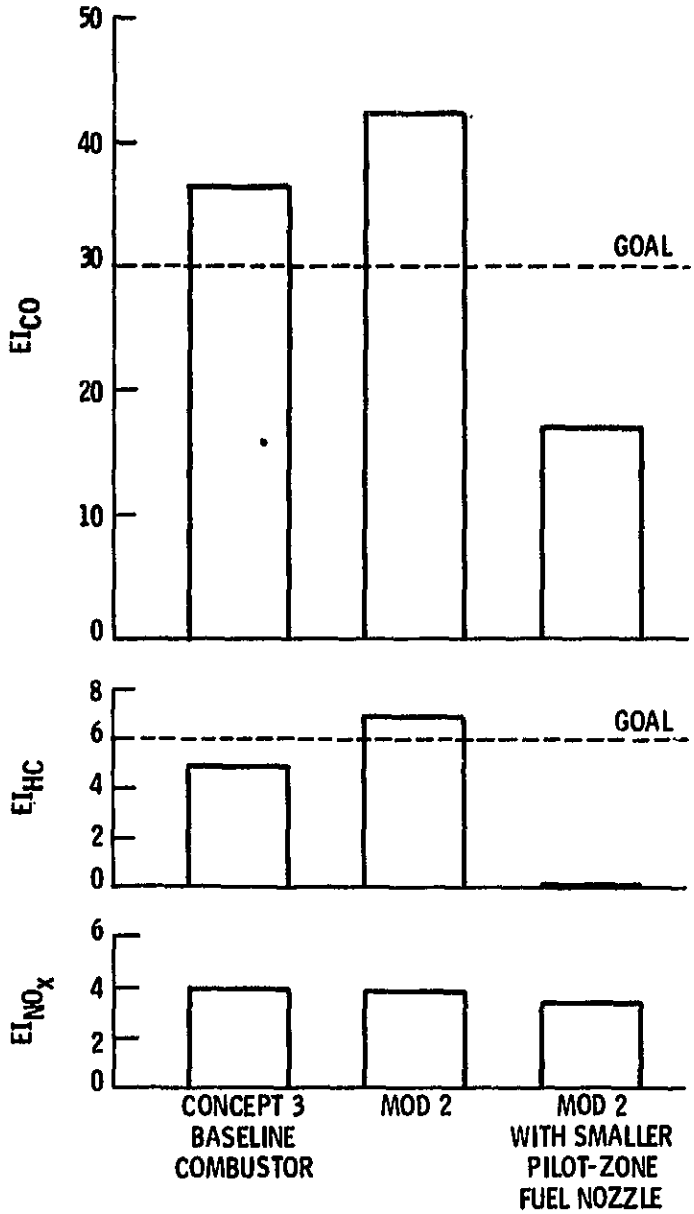


Figure 16. - Concept 3 taxi-idle emissions at design fuel and air split conditions.